IAC-20/C4/10-C3.5 NUCLEAR THERMAL ROCKET WITH FISSILE AND REACTION FUEL FROM LUNAR ISRU

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ABSTRACT

A nuclear thermal rocket (NTR) fueling concept is presented for the first time in which the earth-launched components are completely and totally free of radioactive materials. This is a crucial enabler to fast transport around the solar system as it will allay a great many concerns from private citizens and from competing nations. Outlined here is the use of lunar thorium and water ice to provide the fissile uranium and hydrogen reaction mass needed for a high performance NTR capable of reaching Mars or main belt asteroids in four months. In this way, an ordinary machine can be launched from earth, and only fueled when in lunar orbit, far from any concern of radioactive debris falling to earth. Lunar thorium can be concentrated by skull crucible heating because the melting point of thorium dioxide is higher than any other ceramic (3300 K), making it the remainder once the supernatant magma is poured off. Repeat refinements can be used to achieve high purity. The concentrated thorium is readily transmuted by thermal neutrons generated by beryllium when exposed to the high gamma ray flux of outer space, after first being cooled to thermal energies by a graphite moderator. Fertile thorium transmutes to protactinium (Pr^{91}), which can be selectively removed by the THOREX process. This unstable atom decays with a half life of 27 days into U-233 which is a fissile isotope with the desirable property of producing short-lived byproducts after being used as a nuclear fuel. Compressed pellets of uranium dioxide are built into fuel rods for suitably-designed NTR systems. The hydrogen reaction mass for the NTR can be obtained from water ice harvested in permanently-shadowed regions of the moon and stored in solid-state porous silicon media, a process subject to four US patents. Hydrogen can be stored for extended durations, and released on demand using reactor heat. A portion of the hydrogen fuel can be stored in two-meter thick shell sections to provide radiation protection for crew. The hydrogen therein could be withdrawn as a back-up supply of fuel, or for a final Hohmann transfer burn just before refueling. With both uranium and hydrogen supplied from the moon, this concept can produce abundant fuel for rapid transport around the solar system without any risk of dispersal of hazardous materials during earth launch. This breakthrough could help usher in a transformative tipping point in the exploration and exploitation of outer space.

INTRODUCTION

Space travel beyond the earth's protective magnetosphere is hazardous to humans and to electronics because of the pervasive and diverse forms of space radiation. Trips to the Moon are exposed to deep space radiation and solar particles for over half of the three-day journey. Trips to Mars or main belt asteroids mean months of heavy exposure. The answer is speed, shielding, or both.

This study covers a second generation fission fuel fabrication process to power a nuclear thermal rocket (NTR) using raw materials beneficiated from lunar regolith. Also explored is long-duration storage of hydrogen reaction mass using a separate method of in situ resource utilization (ISRU). This solid-state storage can serve as a radiation shield, advantageously built into a shell surrounding a crew capsule and other sensitive payloads. The combination of high exhaust velocity and protection from ionizing radiation support a long-serving propulsion system, capable of refueling at many locations within the Solar System.

Our motivation is to avoid the launch of any radioactive materials from the surface of the Earth. Commercial and industrial operations could safely operate, with a wide variety of entrepreneurial opportunities available, at negligible risk to terrestrial inhabitants. The vital elements of thorium, silicon, and hydrogen are advantageously exploited in a holistic ISRU operation designed to enable rapid, safe, economical transport through outer space.

A companion paper in this conference explores the first generation nuclear reactor on the moon using simple processing techniques. This paper explores a more refined and exacting lunar surface operation to make precision fuel pins for a compact NERVA-class NTR. The commonality in both approaches is transmutation of thorium into uranium using the abundant gamma ray fog pervading deep space. The oxide of fissile U-233 is pressed into pellets, clad in metal rods, and delivered to a spacecraft propulsion system in which everything except the fuel, and the hydrogen storage, was built on Earth.

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METHODS

Lunar Resource Extraction (LuRE)

Lunar thorium, as with terrestrial thorium, is contained within the crystal lattices of minerals. While several mineral structures are known to contain thorium ions, the relatively abundant mineral monazite ($ThPO_4$) will be used as a general term for any thorium-bearing minerals present in the lunar regolith and subsurface geologic material. It should also be noted that since the operations described in this section represent the second-generation of lunar nuclear reactor operations, the requisite water for all aqueous chemical extraction processes will be attained from the first generation operations which will allow for the retrieval of liquid water from the ice present on the lunar surface.

Thorium bearing minerals will first need to be separated from the bulk of the lunar regolith. Using jaw crushers, (i.e. the H2550 Telsmith Hydra-Jaw Crusher system [29]) the lunar material will be reduced in size and may even be passed to secondary crushing systems (gyratory crushers) and screened to ensure the proper grain size is achieved. The proposed crushing systems are based on terrestrial operations but the chosen crushing systems will be adapted specifically to minimize the challenges posed by reduced gravity (reduced throughput) and mostly un-weathered geologic material (increased risk of blockage). By designing a crushing facility with these limitations in mind, maximum throughput and crusher efficiency will be achieved by running the crushers at or near full capacity whenever possible as well as reducing the material in size mostly in the primary crushing step [30].

Traditionally, the process of extracting thorium for use as nuclear fuel is carried out using the THOREX process [10]. In terrestrial operation, this process requires the fuel to be dissolved into an aqueous solution. A feed solution is then prepared, and co-precipitation processes are executed to extract the fuel from the aqueous phase. The fuel then undergoes purification cycles before it is oxidized into a powder and packed into fuel pellets [28]. However, since terrestrial processes begin with pre-cladded pellets of fuel-bearing material, the initial decladding processes are replaced with hot basic and acidic solutions in order to bring the thorium fuel into an aqueous solution [19].

Stage I: Crucible heating analysis

An RF induction heater is used to heat up the monazite-rich regolith to gather a higher concentration of thorium. The desired result is to heat the regolith to a high enough temperature where the majority of its components reach a molten state, while leaving ThO_2 in its solid state due to the high melting point of 3300 K [32]. This will concentrate the heavy compound to the bottom of the crucible which will remain after pouring out the supernatant magma. A conservative high temperature of 2250 K for the regolith is set as the goal for the crucible to ensure a majority of the mass is brought to the liquidus point.

The power, energy and time required was calculated by using a one-dimensional thermal simulation study of the regolith within the crucible. The finite element simulation was modeled by solving a first-order approximation to the transient heat conduction equation [33]:

$$\frac{dT}{dt} = \frac{k}{c\rho}\left(\frac{\partial^2 T}{\partial x^2}\right) \quad (1)$$

Where T is temperature, k is thermal conductivity, c is specific heat, ρ is density, and x is the distance variable. The temperature increase with time due to the induction coils is considered using Fourier's law:

$$T(x, t+\Delta t) = T(x,t) + \left(\frac{k\Delta t}{c\rho}\right)\left[\frac{\partial^2 T}{\partial x^2} + \dot{Q_{in}}\frac{\Delta x}{kA}\right] \quad (2)$$

Where A is the area of the finite element and $\dot{Q_{in}}$ is the heater power. The heater power is dependent on the rate of change in the magnetic field experienced by the finite element, at a certain temperature, induced by the rate of change in the current flowing through the induction coils.

The physical properties considered are that of the Apollo 12 samples. The temperature-dependent thermal conductivity of the regolith is given by [34]:

$$k = 0.000922 + (3.19 * 10^{-11})T(x,t)^3 \frac{W}{mK} \quad (3)$$

The variable heat capacity is given by [23]:

$$c = -1848.5 + 1047.41 log\big(T(x,t)\big) \frac{J}{Kg.K} \quad (4)$$

The heater power, $\dot{Q_{in}}$, input for a finite element is determined using the electrical conductivity and electric field [35]:

$$\dot{Q_{in}}(x, t+\Delta t) = \sigma E^2 \Delta V \quad (5)$$

Where E is the electric field, ΔV is the finite element volume and σ is the electrical conductivity. The electrical conductivity of the regolith is taken to be 1 mho/m between the temperatures of 0K to 1445 K, and to be 5 mho/m for temperatures above 1445 K [36]. Using Faraday's equations 6,7) and radial equation for current (8), we can reduce the expressions to equation (9).

$$\frac{dE}{dx} = -\frac{dB}{dt} \quad (6)$$

$$B = \mu\frac{NI}{t} \quad (7)$$

$$I = I_{max} cos\,(\omega t) \quad (8)$$

$$dE = \mu(NI_{max}) w sin(\omega t) \quad (9)$$

Where B is the magnetic field, μ is the magnetic permeability. For the induction coils, I is the current, I_{max} is the amplitude of the current, N is number of turns and ω is the RF frequency.

Constants	***Value***
ρ	1300 Kg/m^3 [36]
w	84,822,662 rad/s (typical)
μ	0.000201 H/m [37]

Table 1. *Constants used for finite element analysis.*

Active cooling is required to ensure a skull of unmelted matrix around the molten regolith. The heat removal power depends on the ambient temperature as well as the regolith's surface temperature. Using the specific heat capacity of the refrigerant (c_p), the inlet and outlet temperature difference of the cooling coils (ΔT) and the heat removal power required, we can calculate the mass flow required ($\dot{m}$).

$$Q = \dot{m}\, c_p\, \Delta T \quad (10)$$

The low temperatures of the lunar surface at night allow radiative heat transfer to aid in the formation of a "skull", obviating the need for a separate crucible. Water can be used to cool the coils even below its freezing point by utilizing a glycol percentage of 30-40%.

The finite element analysis was done using Excel™ and it's optimizer function to provide the minimum power required. The individual cells of the worksheet were treated as the finite element whose temperature depends on its own heat capacity, thermal conductivity, electrical conductivity and on the temperature of its neighboring elements. The heat power required to raise the temperature of the element to the required value at a given instant was calculated using equation (5). The one-dimensional thermal analysis was modeled along the diameter of the crucible which was then used to estimate the total electrical power required for the induction heater as well as the cooling coils.

The required minimum power was realized by manipulating the (NImax) term to reach the desired liquidus temperature within a reasonable time period. Once the majority of the regolith's mass has been made molten, we can expect the highly-dense thorium containing compounds to settle to the bottom of the crucible, while low density refractory compounds such as MgOx and CaOx will float to the top. These compounds can be skimmed away, and the rest of the supernatant magma can be poured off exposing the thorium-rich solids. If needed, these can be gathered and refined again using a second skull heating operation to boost the purity even further.

Following the concentration of thorium-bearing material via crucible heating, the material is prepared for solvent extraction by being decomposed in hot, aqueous sodium hydroxide (NaOH). The hydroxide is further mixed with hydrochloric acid (down to ~ pH 3 [27]) which results in a thorium rich solid precipitate ("thorium cake"). This cake is then dissolved in nitric acid with hydrofluoric acid trace (~ 13 – 15 M HNO_3 with 0.03 – 0.05 M HF and 0.1 M $Al(NO_3)_3$ [28]) which results in a Th-bearing acidic solution (~ 20 g/L Th with ~ 8 – 9 M [19]). Fluoride salts (i.e. NaF, KF) have also been used in place of HF and may be substituted if HF proves more costly to transport to the lunar surface than the *in situ* synthesis of such salts.

Stage II: Separation

Following dissolution, the thorium-bearing solution is admitted within a graphite-lined beryllium shell and placed on the lunar surface so as to be exposed to the isotropic gamma ray "fog" of deep space. When gamma rays of 0.1 MeV and greater impinge on the Be shell, neutrons are generated. The graphite moderator slows the neutrons until they are in thermal equilibrium with the matrix. Such "thermal" neutrons can be captured by the thorium nucleus, making a new isotope of thorium. Within minutes this thorium isotope decays by beta radiation and transmutes into protactinium, element 91. Protactinium is unstable, and decays with a half life of 27 days into the isotope of uranium with atomic mass of 233, as shown in equation (11).

$$^{232}_{90}Th + n \rightarrow {}^{233}_{90}Th + \beta^- \rightarrow {}^{233}_{91}Pa + \beta^- \xrightarrow{27\ days} {}^{233}_{92}U \quad (11)$$

Once the transmutation runs to completion, the material is moved to a new container for solvent extraction. Solvent extraction requires the mixing of two phases of solution, one aqueous and another organic. For these operations, the solute (aqueous phase) is the uranium present in nitric acid and the extractant (organic phase) is a diluted amide such as tributyl phosphate (TBP) [20].

TBP dissolves uranium only at low concentrations (3-7%), while at higher concentrations it dissolves thorium and must be diluted in n-dodecane. Multi-stage chemical strip columns, or centrifugal contactors, are used to shuffle byproducts in and out of the countercurrent TBP and actinide-bearing nitric acid streams.

TBP will eventually decompose into its dibutyl- (DBP) and even monobutyl- (MDP) forms, or decompose all the way to phosphoric acid under severe radiological and thermal processing. Alternate solvents can be used which are easier to synthesize than TBP, e.g. N,N-dialkyl amides [9]. However, such extractants require more intensive recycling processes, which have historically been studied in far less detail than those utilizing TBP. We selected the TBP-based

material processing to adapt to operations on the lunar surface because of the ability to recycle this organic phase. With the same hardware, and modest changes to the process (i.e. chemical constituents or modification of extractant concentration), this approach can selectively remove thorium for purity or uranium for fuel. Recovery of un-transmuted thorium can help reduce unwanted side reactions producing U-232. Uranium is extracted in a form that can be converted to urania, which is then packed into fuel pellets.

Once the mixture has reached the desired loading concentration, the feed, scrub, and stripping mixtures are added sequentially, and the spent solvent is sent for recycling along with the raffinate [26]. The result of this process is a solution dominated by uranyl nitrate ($UO_2(NO_3)_2$) [10].

Stage III: Precipitation and Calcination

Uranium, and the thorium remaining in solution, are co-precipitated using NH_4OH and calcined (at ~600° C), resulting in the compound $ThO_2 + U_3O_8$. This material is then reduced in a hydrogen environment (at ~800° C) which produced a $ThO_2 + UO_2$ powder [31]. The powder is then characterized to ensure high purity, compressed, and sintered into discrete packets, before being sent for consolidation and fabrication of the target material [26].

Stage IV: Containment, Recycling, and Reprocessing

In mining and resource extraction operations, the re-use, recycling, or repurposing of constituents can be crucial in ensuring the economic and ecological feasibility of an operation. On the lunar surface, ecological concerns are limited (though not non-existent). However, economic considerations are crucial to the success and continuation of any space mission, being driven largely by soft-landed mass. High costs can and should be anticipated when undertaking a mission in orbit, on extraterrestrial surfaces, or generally in outer space.

The economic impact of launch/landing costs, plus the duration, are studied for all operations. Reprocessing involves many steps, many chemical reagents, and careful control. The cost and yield of reprocessing to recover/recycle thorium and to extract fissile U-233 must be considered together with the cost of extracting and beneficiating the raw ore.

For the bulk of the processing facility, polypropylene will be used to contain and facilitate reactions wherever possible. This will be used in lieu of low-carbon stainless steel (e.g., SS304L) due to the lower density. However, stainless steel or superalloys (e.g., Hastelloy® or Inconel®) will be required for certain piping and containment of certain processes, because of their resistance to corrosion in the concentrated acids.

Initially, the full required mass of TBP will be shipped to the lunar surface. However, TBP may also be recycled on the lunar surface.. The recycling process begins with the capture of the CO_2 and some of the NO_x produced during calcination which is fed to cyanobacteria. The carbon monoxide and hydrogen produced by the cyanobacteria is synthesized into hydrocarbon intermediates (via Fischer-Tropsch or similar). The remaining NO_x as well as gaseous phosphorous (captured during skull melting) are bubbled through water producing and recovering nitric and phosphoric acid, respectively. The combination of the hydrocarbons and acids are used to synthesize TBP by [39]:

$$POCl_3 + 3\,C_4H_9OH \Rightarrow (C_4H_9O)_3PO + 3\,HCl \qquad (12)$$

Following the synthesis of the crude TBP product, the washed organic phase is separated and the excess *n*-butanol present in solution is recovered. The crude product is then purified of the residual *n*-butanol, mono-phosphoric acid, di-phosphoric acid, water, and other impurities which form during synthesis. Final purification is carried out via batch distillation under vacuum. Under low vacuum, the *n*-butanol and water constituents are removed (these constituents are also sent for *n*-butanol recovery). Following this removal stage, the purified TBP is transferred to a holding tank and is ready for re-use [40].

Overall, the mass of the required materials for this stage of operations is approximately 11 metric tons. The subsystem component masses are presented in Table 2.

Reactants, assumes H_2O in situ:	**0.0865 MT**
H_2O | harvested in situ	0 kg
NaOH | shipped as solid	7.0 kg
HCl | as 6M solution	24 kg
HNO_3 | as 13 – 15M solution	21 kg
TBP | diluted in n-*dodecane*	27 kg
Oxalic acid | as 0.5M solution	7.5 kg
Facility, consisting of:	**10.6 MT**
Reactant containment vessels	3.1 MT
Crushers [39]	7.5 MT
TOTAL	**10.7 MT**

Table 2. Mass analysis of THOREX facility.

Lunar THOREX Challenges

The adaptation of the THOREX process to the lunar surface will be beset by challenges. Mineral and material extraction operations on Earth have the benefit of an oxygen rich atmosphere, sealed facilities with temperature control, repair crews, and expansive areas where operations can take place. On the lunar surface, none of these benefits will be available and the inherent physical properties of the lunar surface ensure that high strain is put on our systems. Only through thorough prediction and planning can these challenges be

controlled. A select list of challenges faced by the adapted lunar THOREX process, along with proposed solutions, can be seen in Table 3. The solutions presented open a pathway to successful radiochemistry processing on the Moon.

Challenge	***Symptoms***	***Solution***
Temperature (-200 to +250° C over full day/night cycle)	Stress on electronics, risk of freezing or boiling (of chemical constituents)	Controlled environments and utilization of heat by-products (skull crucible, radioactive decay, etc.)
Low gravity (~ 17% Earth's)	Inefficient gravity-driven processes	Multi-stage crushing & sorting
Limited space (components require housing and shielding)	Inability to perform certain operations (i.e. heap leaching)	Controlled environments and small batch processing

Table 3. Challenges & solutions for lunar-based THOREX.

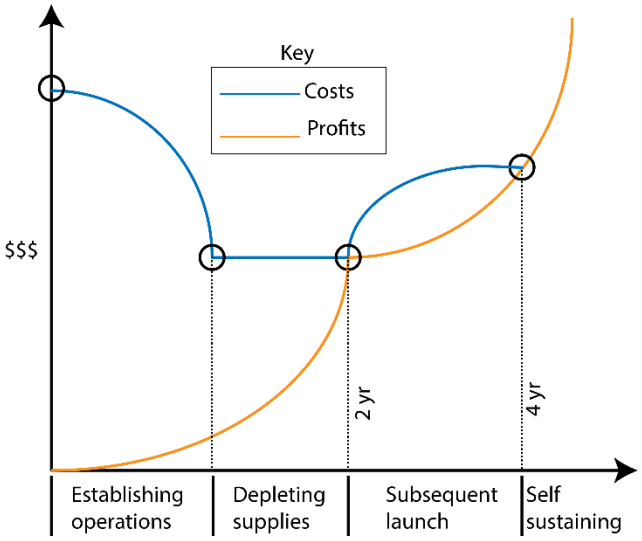

Figure 1. General cost-analysis for operations

ISRU-based Hydrogen Storage
Hydrogen reaction mass for the NTR can be stored in a solid-state using catalytically-modified porous silicon [1-7]. Silicon comprises 21% of lunar regolith and can be extracted using an isotope separation process similar to mass spectroscopy [11-14]. A self-contained apparatus can produce the storage media using only in situ resources [8]. A low-energy, long-duration, solid-state-absorbed hydrogen storage system wrapped around the crew quarter of a NTR can provide protection against space radiation. Such a hydrogen storage system can be recharged at many locations within the Solar System, requiring only water ice and an electrolysis apparatus to separate out hydrogen. Recharge requires just 0.8 MPa, and release requires just 120 ºC.

Reactor Propulsion Design
The configuration and design of the initial reactor core will largely be based on the work of the NERVA program and model analysis performed by Belair, et al. [41]. The difficulties in establishing operations on the moon necessitates well researched and tested designs for early use. Of the four models covered in [41] two were compatible with highly-enriched lunar uranium processed as described above.

The two designs considered for our purposes were a small NERVA engine and a large Nerva engine. The small NERVA requires 27kg of uranium and uses a 1:1 tie-tube to fuel element ratio. The large engine requires 36kg of uranium and uses a 2:1 fuel element to tie-tube configuration [41]. The smaller of these engines delivers a total of 152.5 MW of thermal power and delivers 33,200 N of thrust using hydrogen reaction mass through a converging-diverging nozzle of area ratio 300:1. As production of uranium improves, moving to the large NERVA engine would be preferable with its higher thrust to weight ratio, and slightly higher specific impulse. Rocket and trajectory calculations were performed based on producing 27 kg of U-233 after four earth years.

Mass of Hydrogen
The mass of hydrogen required is calculated using the Tsiolkovsky rocket equation and an exhause velocity of 8829 m/s [41]. The velocity change (Δv) required is calculated with the vis-viva equation (also known as the orbital-energy-invariance law) and an assumed Hohmann Transfer [43]. Additionally, balanced momentum and energy equations were used to calculate burn time and power delivery. The mass of hydrogen can be reduced with the utilization of a LANTR (liquid oxygen-augmented nuclear thermal rocket) system. The LANTR utilizes oxygen to create a supersonic combustion after the hydrogen exits the core. The benefit is a greater thrust and lower tank storage volume with a reduced specific impulse. Speficially, with an oxygen/hydrogen mass ratio of 7/1, one can achieve a thrust increase of 440% with only a 45% reduction in specific impulse. Importantly, the tank volume decreases significantly [40].

Fuel Delivery Method
Three major options are considered for delivery of our fuel and propellant. Each involves meeting the payload in low lunar orbit. Landing the payload on the lunar surface for delivery of fuel is not considered due to the exponential

growth in required hydrogen propellant. The three options evaluated for this paper were:

1. Chemical booster to Low Lunar Orbit (LLO)
2. Reusable NTR tug from surface to LLO
3. Modular propulsion system, self-delivered to LLO

Low lunar orbit here is assumed to be 100 miles above the surface.

Reactor Subsystems, Fluid Flow and Heat Dissipation
The fission reactor at the core of the NTR has many subsystems. We studied the hydrogen flow system, the reactor fuel pin packaging and neutron mirrors, the nozzle/exhaust system, and thermal load shedding for heat dissipation of a variable thrust system.

The Hydrogen Flow system: To extract the hydrogen from the solid state storage, the storage tank is heated and the escaping hydrogen is collected and sent through a pipe through to the next stage. As the released hydrogen is of low pressure, in the range of 116 psia (8 bar), the hydrogen pressure must be increased using a suitable compressor. The preferred type of compressor should be oil-free with a compression ratio greater than 10:1. The hydrogen flow into the reactor is then split such that $1/5^{th}$ of the cores send out hydrogen into a loop that passes through a heat exchanger and then returns back into the reactor to be heated, mixed with oxygen and exhausted out of the nozzle to provide thrust.

Reactor heat dissipation: The nuclear core produces a large amount of thermal energy, much of this is used to provide thrust for the rocket but a small fraction of it is used to power critical systems in the rocket. As this subsystem also includes radiators to cool down the thermodynamic fluid after it passes through the heat exchanger and turbomachinery, it is preferred to use a secondary thermodynamic fluid that is of a liquid or molten salt nature so as to mitigate the risk of fluid loss following micro meteor impacts. This subsystem begins at the storage tank for the secondary thermodynamic fluid or coolant and then flow splits into two, a small amount of the coolant flows into the pump and compressor used to draw out the hydrogen from the solid state tanks. The remaining coolant flows into a heat exchanger that absorbs the thermal energy form the hydrogen that recirculates the reactor core, this coolant then proceeds toward the turbine-pump setup and generates electricity required for the vessel. The coolant then passes through a flow control tank and then into the radiators outside the main body of the rocket. The reactor then cools down by radiative heat transfer into deep space and the working fluid returns to the main coolant tank.

RESULTS

Crucible heating analysis

Assuming the initial temperature of regolith to be -17 °C and ambient temperature of the lunar surface at night to be -195 °C, a Cold Crucible RF heater would require 1.621 MWh of energy, with a variable power range of 51 kW to 243 kW as shown in Figure 2, to bring 90% of 1,861 kg of regolith to 2250 K in 20 hours. To form a skull around the molten regolith with a thickness of 6 to 7 cm would require an average of 270 W of heat removal power and 6.2 kWh of energy which can be achieved with a maximum mass flow rate of 0.0082 kg/s of water mixed with glycol (30-40%) operating between 260K and 269K [16-18].

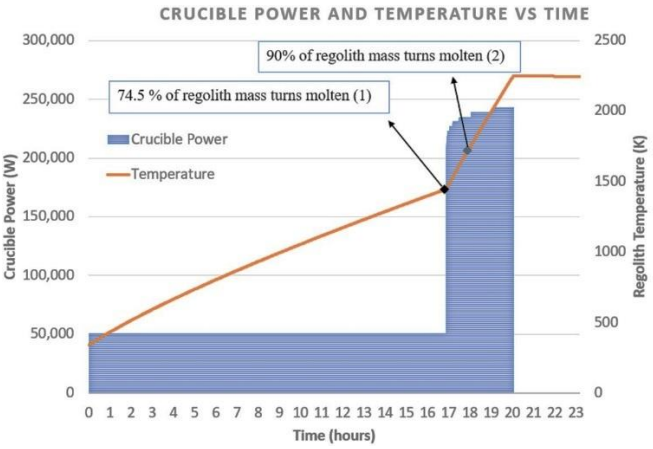

Figure 2. Thermal power absorbed, and temperature of regolith versus time after start of heating.

With an assumed abundance of 20 ppm for thorium in quality ore bodies of regolith [38] it would take 734 iterations to make 27.3 kg of useable thorium if each heated charge is two meters in diameter and two meters deep. The total energy requirement is 1.19 GWh. The mass of the total apparatus was calculated to be 290 kg, including the transformer, supporting alumina crucible and induction coils. One such crucible system would require 613 earth days to process sufficient material. This time can be reduced dramatically if multiple crucible systems are brought to the manufacturing site.

Resource Extraction Facility Analysis
Based on the output from the skull crucible, a single resource extraction facility can produce the requisite 27.3 kg of radioactive material after approximately 2 years. Overall, the production of this material will necessitate 1937 iterations of the aqueous, calcination, and sintering processes described in LuRE stages I-III and will require 20 kW of baseload power. Adaptations may be made to the design of this facility in future operations to suit the specific time, energy, and weight requirements of those missions.

Mass of Hydrogen
Velocity change from LLO to low Mars orbit is 3410 m/s and the exhaust velocity of the small NTR is approximately

8829 m/s [41]. From the rocket equation, this gives us a wet mass to dry mass rations of 1.47. With a dry mass of 400,000 kg, this would require 188,600 kg of hydrogen propellant. From our initial and final masses and velocities, we find that the total change in momentum is 1.06 x10^9 kg*m/s. With the small NERVA thrust of 33200 N, this gives a burn time of 8.83 hours.

Adjustments for LANTR system

One method for reducing the amount of hydrogen is the use of liquid oxygen to combust with the hydrogen in the nozzle chamber. Figure 3 is a graph on the effect of oxygen on the mass of required hydrogen.

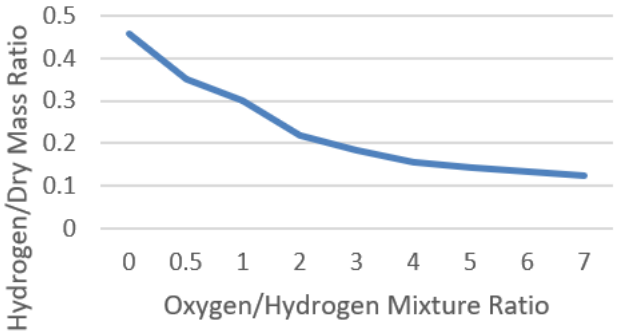

Figure 3. Oxygen effect on hydrogen mass ratio

The hydrogen can be reduced from nearly half the dry mass, to as low as 12% of the dry mass. This would be about 48000 kg of hydrogen with our system. Though a lower oxygen/hydrogen mass ratio is likely to be utilized to avoid the high mass of oxygen.

System Delivery to Customer

Of the three potential methods for delivering our fuel and propellant to customers, the best for our purposes would be the use of a reusable chemical engine. This avoids the necessity of a higher amount of initial uranium and is easier than completely assembling our nuclear engine on the lunar surface.

The delivery of 188,000 kg of hydrogen and 27 kg of fuel would require an additional 115,000 kg of propellant for the chemical rocket. Eventually, a second NTR system will be used for delivery. This would only require an additional 54000 kg of propellant. Both options are preferable to landing on the moon and taking off as that would require 309,000 kg of pure hydrogen propellant. Clients will launch from Earth with our NTR (minus UO_2) already attached to their upper stage. Our delivery system will launch to meet with their stage in LLO. Once they are docked together, our fuel rods can be placed into the core of the NTR and the hydrogen tanks can be filled.

Comparison with Chemical Rockets

It is important to note the benefits of the NTR over traditional chemical rocket engines. The higher thrust is beneficial for the higher delta v of escaping Earths gravity, but with a lower delta v required for escaping lunar orbit, the higher specific impulse of the NTRs is preferable. A comparison of the delta v for a standard chemical rocket as well as the small and large NERVA engines can be found below.

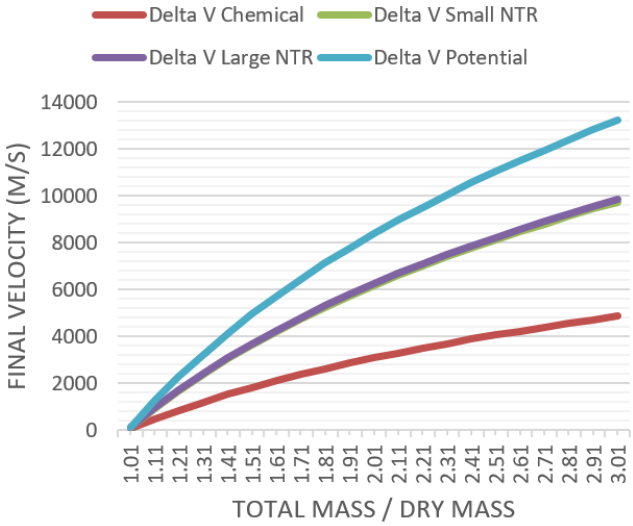

Figure 4. Oxygen Effect on Hydrogen Mass Ratio

Reactor Subsystems, Fluid Flow and Heat dissipation

Refering to figure 5, the hydrogen flow system has been designed in such a way that the pipes remove the hydrogen from the tanks (1) through inductive heating. Exit pressure of 116.03 psia hydrogen enters a compressor pump (2), specifically a guided rotor compressor, and exits the compressor at a pressure of 1500 psia. This high pressure hydrogen is then temporarily stored in a pressure tank (3) to be used when thrust is demanded. From the high pressure tank (3) the hydrogen then flows into the reactor core (4) after passing around the nozzle (6) to ensure it remains cooled. The hydrogen then splits before flowing through the reactor core (4), 4/5th of the hydrogen flows through the reactor (4) to the combustion chamber (5) where it mixes with oxygen at a suitable ratio, is ignited, and then flows through the nozzle (6). The remaining 1/5th of hydrogen flows through the reactor core (4) and then into a heat exchanger (B) that transfers the thermal energy to the secondary thermal fluid. The hydrogen then returns to the reactor core (4) where this circulation process repeats.

For the heat dissipation system and energy generation when thrust is not required, a secondary fluid system is considered, due to concerns of loss of gasses due to micro meteor impacts on the radiator panels. After studies into the different heat capacities, density, viscosity and other properties, water was selected as the secondary fluid due to its higher heat capacity and lower density compared to the other fluids and low flow

rate of liquid required to absorb the 32 MW. The water begins at the water storage tanks (A) and then the flow of the water is split and directed into the compressor (2) to cool it and the remaining flow is directed toward the heat exchanger (B) where it absorbs the thermal energy from the hydrogen. The water from the heat exchanger then flows into the turbine (C) where thermal energy is converted into electrical energy in the generator (F), the flows combine and flows through the compressor (D). The water then finally flows into the radiator (E) from where it cools down and returns into the loop. The oxygen flows from the oxygen tank (7) directly into the combustion chamber (5) and out through the nozzle.

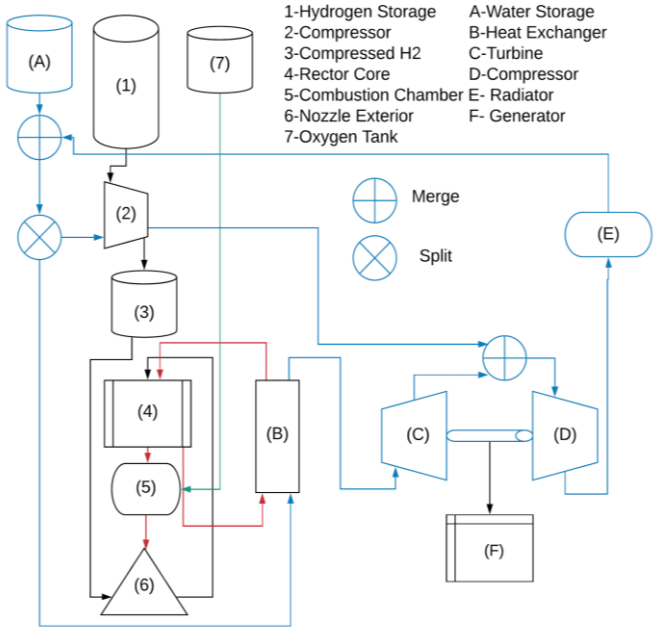

Figure 5. Fluid Flow Diagram

For the design of the radiators a carbon composite type radiator from the work done by Briana N. Tomboulian , et al. Considering 32 MW of thermal energy to be removed from the secondary fluid, and each radiator panel of width 4 meters, thickness of 0.01016 meters and length of 5 meters, the area available per fin and each fin working at an efficiency of 50% due to overlap of area of dissipation from each fin the amount of fins required to remove all heat energy is around 8 fins. The fins are designed to be simple and extendable when the engine exits earth's atmosphere. A side sectional view of the radiator used is given in figure 6.

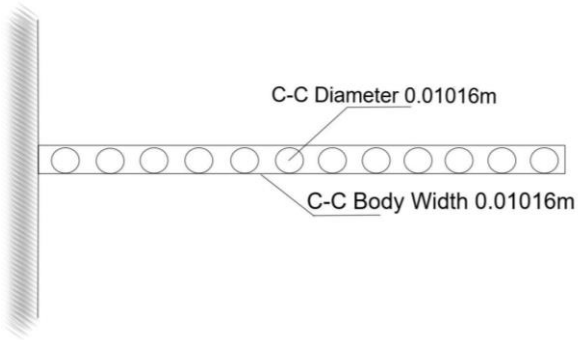

Figure 6. Radiator panel side cross section.

Galactic Cosmic Rays (CGR) are highly energetic photons, subatomic particles and nuclei filling space and coming from every direction. The energy per particle ranges from 1E7 eV to 1E20 eV, although the flux density (particles per square meter per second) falls off exponentially from low to high energy. Figure 7 illustrates how the intensity of 1E7 eV CGR particles are attenuated as a function of the thickness of various shielding materials. Of interest here is the attenuation due to hydrogen and silicon, as these comprise the fuel storage system for the NTR. With a 0.058 w/w ratio of hydrogen to silicon it is apparent that silicon offers the most radiation protection benefits for a reaction mass storage system based on porous silicon.

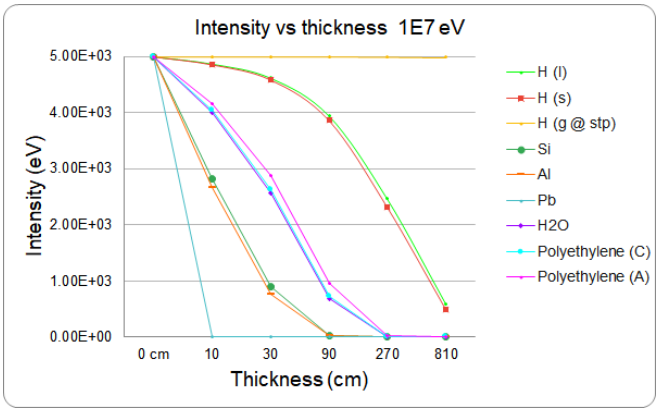

Figure 7. GCR intensity versus thickness of various shielding materials for most-common energies.

A spherical crew volume surrounded by a spherical shell of hydrogen reaction mass stored in porous silicon will reduce GCR flux. A Hohman transfer from lunar orbit to Mars orbit for a 417 MT spacecraft requires 125 MT of hydrogen. The thickness of the hydrogen storage shell depends on the crew volume, so the smaller the volume, the thicker the shell, and the greater the protection against GCRs. Calculations were based on GCRs of 1E7 eV at a flux of 5000/m^2-s through a human body with average cross section of 0.6 square meters, and a relative biological effectiveness of 2.0, for bare protons, which comprise 85% of the GCR flux. In the US, the Occupational Health and Safety

Administration goes by Title 10, Part 20 of the Code of Federal Regulations and calls for a limit of 5 rem per year. With no protection, this limit is reached in less than one week spent in interplanetary space. To meet the OSHA requirements, the GCR flux must be reduced to a 0.0168 fraction. The figure below shows the protection provided by the hydrogen storage system as a function of the volume of crew space for a crew of four transiting from Moon orbit to Mars orbit. Faster ships with more fuel provide greater protection.

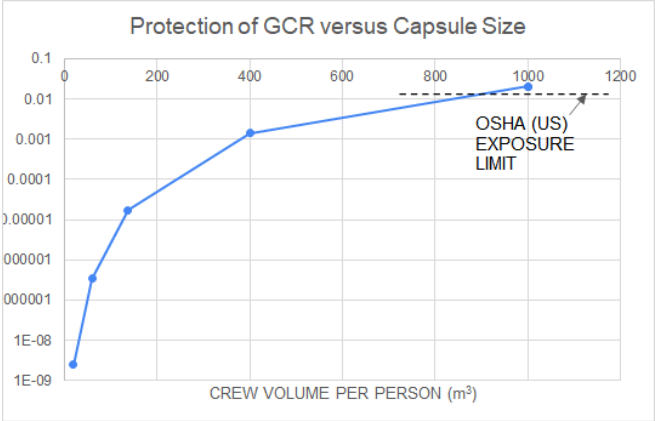

Figure 8. Relative flux reduction from reaction mass storage system versus volume per person, with crew size of four.

DISCUSSION

The mineral resources of the Moon, Mars, and the asteroid belts of the Solar System promise unprecedented wealth for our planet and salvation from our dependence on terrestrial resources. While there is potential for changes in public opinion and governmental oversight regarding the launching of nuclear fueled rockets from the Earth's surface, such a change is unlikely. Our proposed systems will bring extraterrestrial resources within the grasp of our species while promising the same level of safety the public has come to expect from traditional, chemical rockets. Thorough analysis of the challenges we will face, along with our innovative business solutions, assure a going commercial concern.

In our Solar System, there are hundreds of thousands of asteroids available for mining, representing trillions of dollars of resources available for extraction. Modern technologies allow us to discover and characterize asteroids in never-before-seen numbers and detail. Our proposed systems offer an unprecedented opportunity to reach these asteroids quickly and efficiently, extract their resources (or transport the asteroid to near-Earth orbit), and return to Earth.

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